XFEM-Based CZM for the Simulation of 3D Multiple-Stage Hydraulic Fracturing in Quasi-brittle Shale Formations

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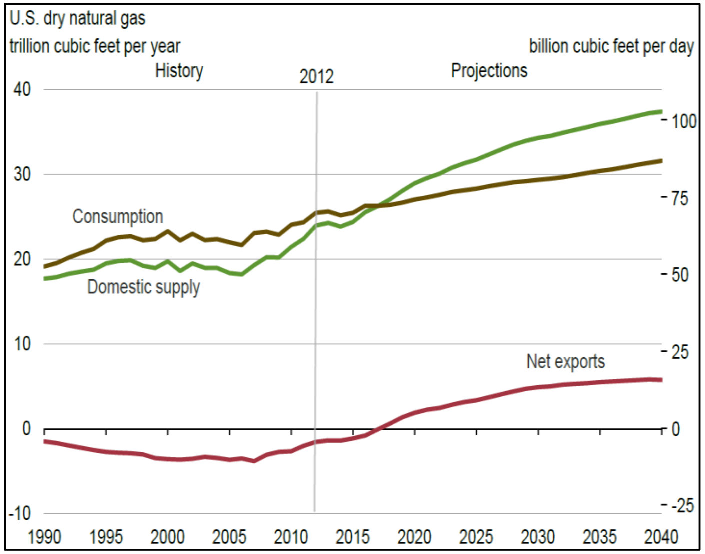
Outline

- Problem description
- Literature review
- Method
- Model Construction
- Results
- Summary and Conclusion

Problem Description (1/2)

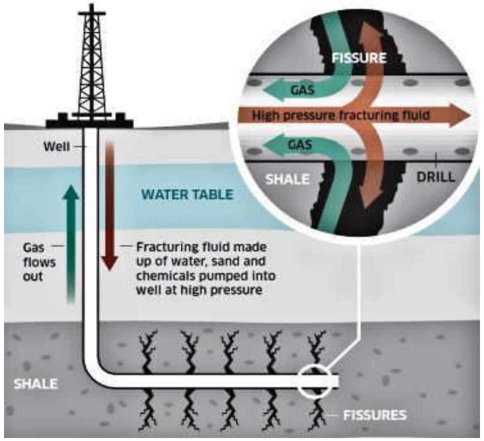
- Profound contribution of shale resources to the prospective independence of the U.S. on oil and gas from foreign resources (EIA 2014)



- Gas desorption: one of the producing mechanisms requiring complex network of fractures
- Production from ultra-low shale permeable rocks possible only through horizontal drilling and hydraulic fracturing
- Motivations for employing numerical optimizing tools: Variety of shale formations, and lack of data, its uncertainty, and cost

Problem Description (2/2)

- **Hydraulic fracturing concerns:**
  - Cap rock at the same place as reservoir – Controlled extension to upper or lower layers – Less environmental effects
  - Demand for more trustworthy long term production estimate

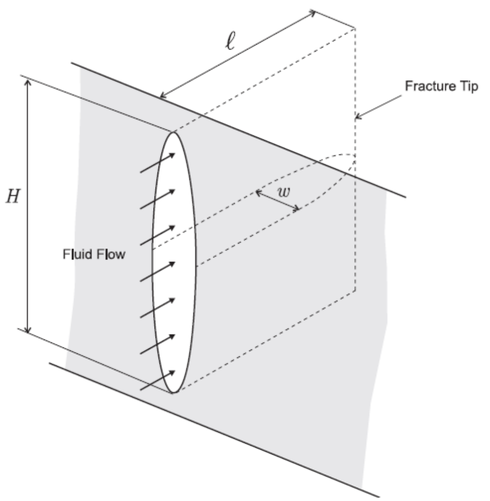


- **Simulation of hydraulic fracturing:**
  - A multi-physics problem coupling fluid flow in the matrix and fracture with matrix deformation and fracture mechanics;
  - Stress shadowing effect
  - Increasingly more complex fracture networks than expected (Weng et al. 2011)

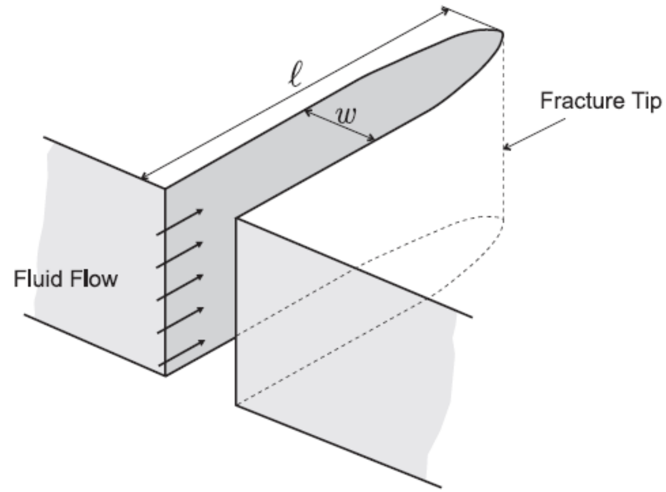
Literature Review: Models and restriction on geometry (1/2)

- Three most well-known 2D analytical models:

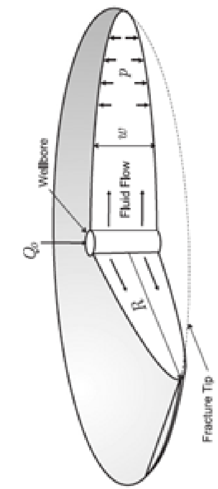
PKN (Nordgren 1972), KGD (Daneshy 1973), and penny-shaped (Abe et al. 1976)



Schematic showing PKN fracture geometry



Schematic showing KGD fracture geometry



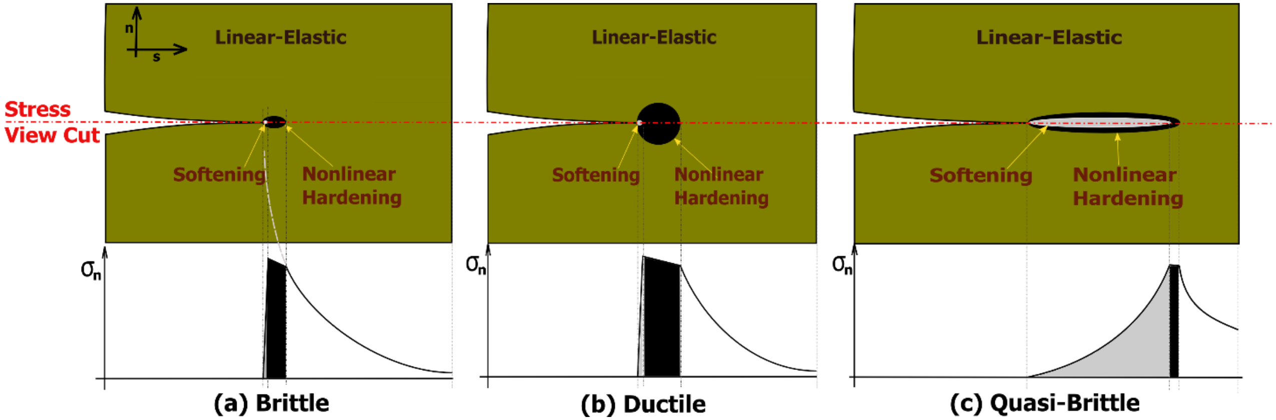
Schematic showing penny-shaped fracture geometry

Ref.: Adachi et al. 2006

- P3DH: Pseudo 3D model (Settari and Cleary 1986). “Pseudo”!

Literature Review: Models and restriction on material (2/2)

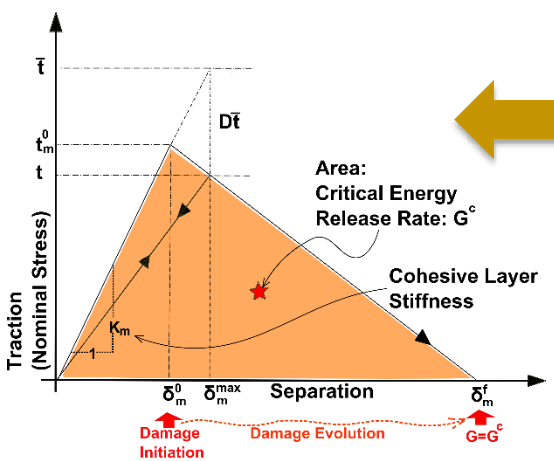
- **The prevailing design tools in hydraulic fracturing applications:** Empirical methods and LEFM-based numerical techniques – good for brittle rocks, conservative results for ductile or quasibrittle rocks; e.g. shales due to neglecting fracture process zone



- Progressive damage in the fracture process zone in quasi-brittle materials. Elastic response abruptly transitions to damage (Bazant 1998).

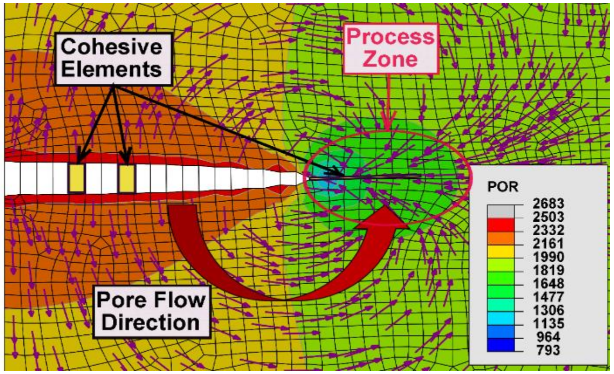
Method: 1-Cohesive Zone Model; a better material model (1/3)

- Cohesive behavior: a better treatment for HF simulations in shales.
- The concept of cohesive zones was applied to fracture modeling for the first time after Dugdale (1960) and Barenblatt (1962)
- Cohesive elements are attractive when interface strengths are relatively weak compared to the adjoining materials (cement in a natural fracture) (Needleman 1987)
- CZM idealizes complex fracture mechanisms with a macroscopic "cohesive law" (ABAQUS 6.12).
- **Planar CZM** with a pre-defined fracture path as the right picture.



Typical cohesive traction-separation law

Typical fully coupled pore pressure-stress analysis using CZM; non-linear porous flow

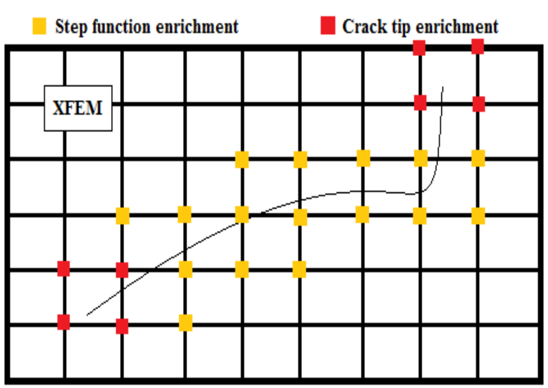


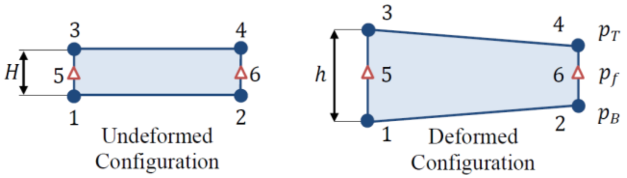
Method: 2-XFEM-based CZM; a better geometrical model (2/3)

- XFEM simulates fracture propagation along arbitrary paths independent of the mesh.
- It uses edge and corner phantom nodes for frac. fluid flow and cohesive behavior.
- XFEM includes a priori knowledge of partial differential equation behavior into finite element space (singularities and discontinuities).

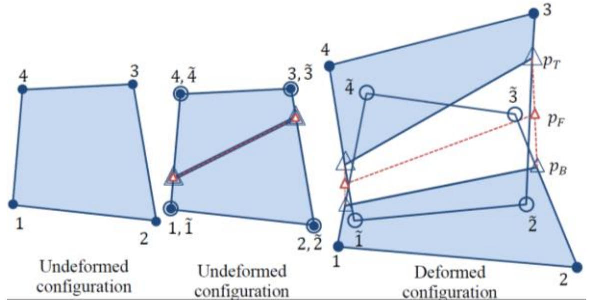
$$u^h(x) = \sum_{I \epsilon N} N_I(x)\left[u_I + H(x)a_I + \sum_{\alpha=1}^{4} F_\alpha(x) b_I^\alpha\right],$$

$$\{F_\alpha(r,\theta)\}_{\alpha=1,2,3,4} = \left\{\sqrt{r}\sin\frac{\theta}{2}, \sqrt{r}\cos\frac{\theta}{2}, \sqrt{r}\sin\frac{\theta}{2}\sin\theta, \sqrt{r}\cos\frac{\theta}{2}\sin\theta\right\}$$





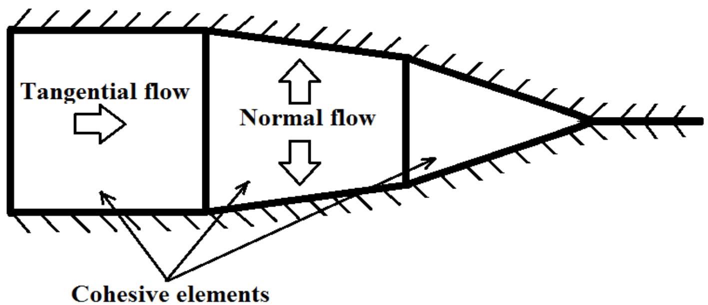
cohesive elements in CZM



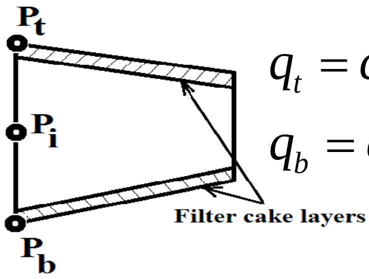
Corner and edge phantom nodes in XFEM-based CZM (Zielonka et al. 2014)

Method: Flow Model (3/3)

- **Leak-off:** Historically assumed uncoupled from the fluid pressure and restricted to linear, 1D flow regimes.
  However, Cohesive Element Flow Model treats leak-off as a <u>fluid component</u> (fully coupled with the other unknowns) calculated from Darcy's or Forchheimer's law based on fluid speed.
- **Fracture, filter cake, and matrix flow:** Reynolds', filter cake, and matrix permeabilities for gap, leak-off, and matrix flows



Tangential and normal flows in pore pressure cohesive elements



$$q_t = c_t \left(p_i - p_t \right)$$
$$q_b = c_b \left(p_i - p_b \right)$$

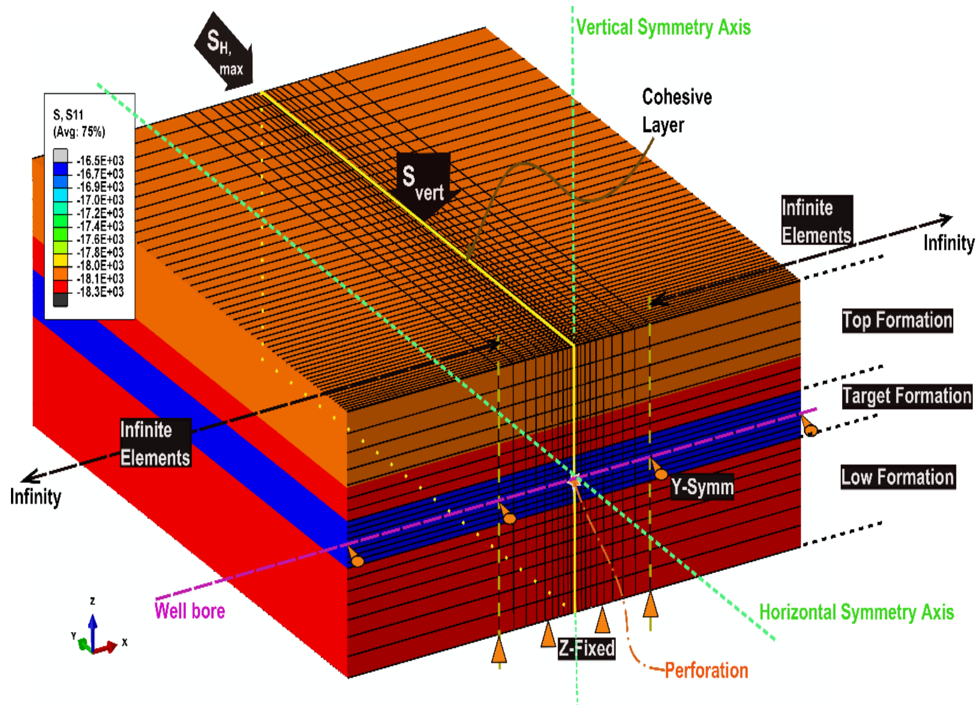
Normal flow or leak-off flow across gap surfaces

- **No Proppant Transport**

Model Construction: CZM (1/4)

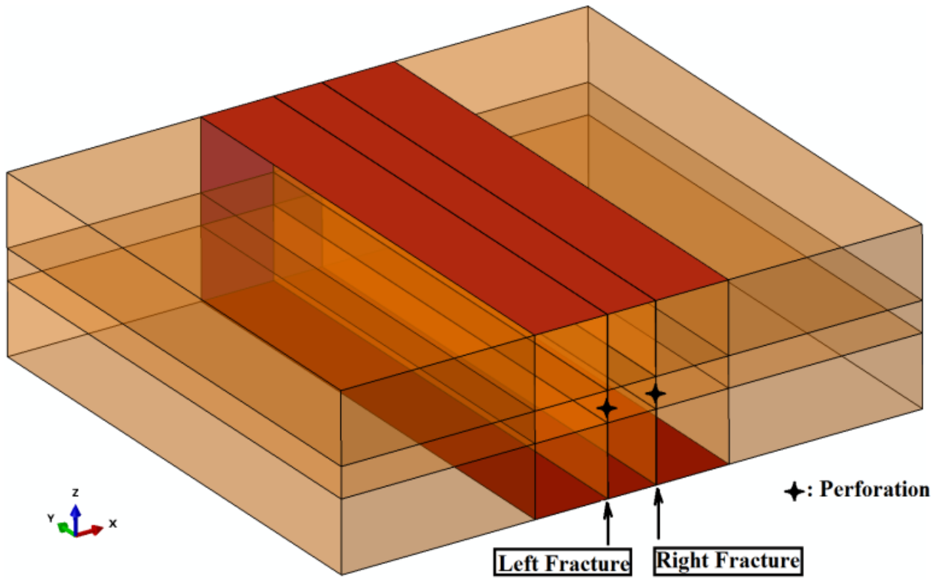
- **Planar single-stage HF in a 3D triple-layer reservoir:**

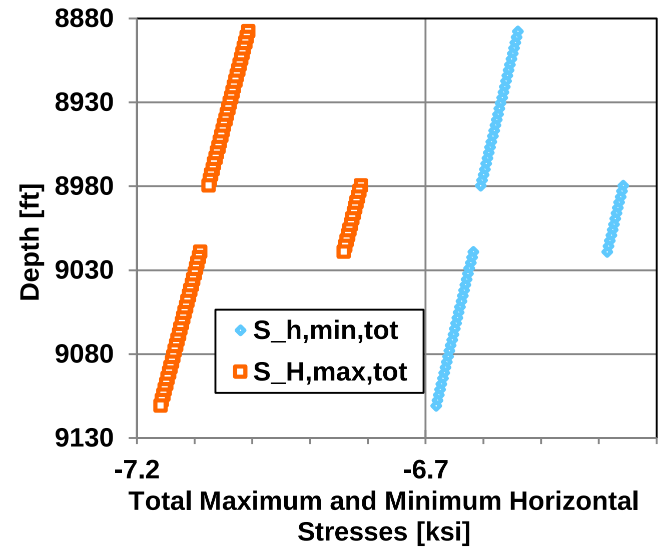
- C3D8RP, COH3D8P, and CIN3D8 elements for rock, fracture, and infinite domains, respectively.
- Fracture space is modeled by initially closed cohesive elements on a plane perpendicular to minimum horizontal stress.
- Fully coupled pore pressure-stress, quasi-static, finite strain analysis



- XYZ = 197, 689, and 224 ft
- The infinite elements are 197 ft long

Model Construction: Double-stage (2/4)



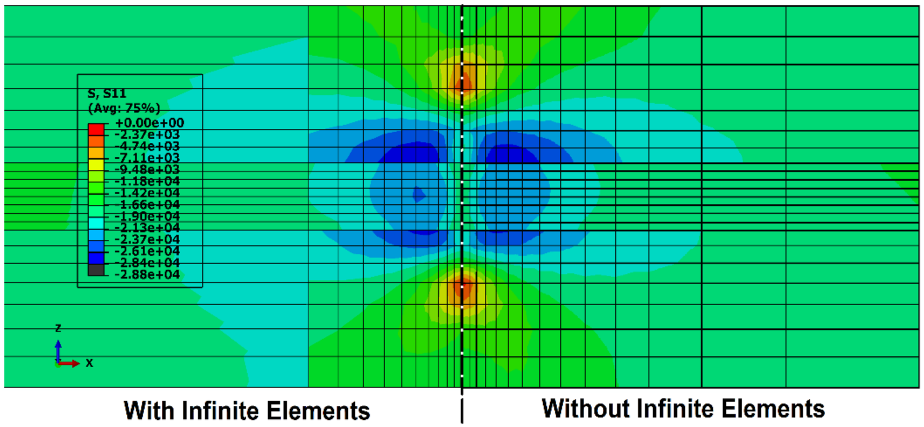


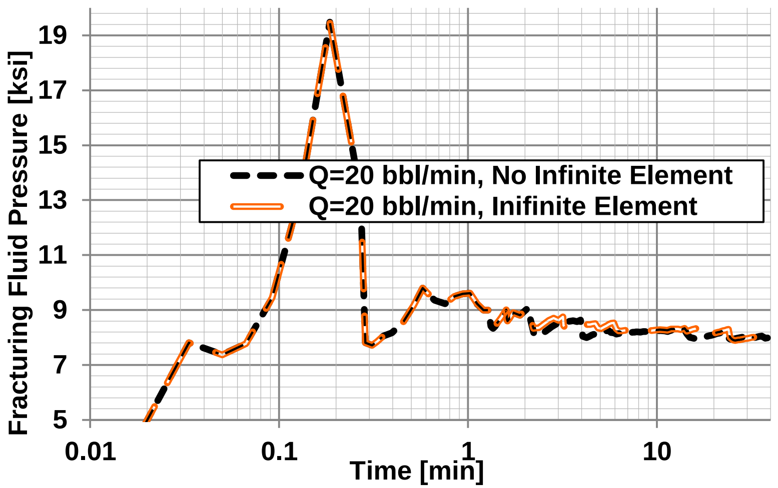
Property	Value
Min. and Max. Horiz. stress	~ -6400 psi, -6800 psi
Porosity, Eff. Permeability	0.142, 0.5 mD
Young's Modulus and Poisson's Ratio	3 Mpsi, 0.27
Depth and Thickness	9000 ft, 224 ft
Drucker-Prager Friction and Dilation Angles	36, 36

Parameter	Value
Pump Rate [bbl/min]	40
Injection Time [min]	20
Number of Perforation Clusters	2
Cluster Spacing [ft]	0 (default, single cluster), 33, 66
Injection Fluid Density [kg/m^3]	1000
Viscosity [cp]	5
Gravity [N/kg]	10 (in negative z direction)

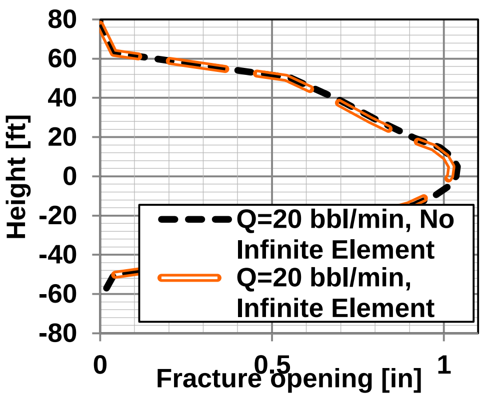
Model Construction: Infinite Elem. (4/4)

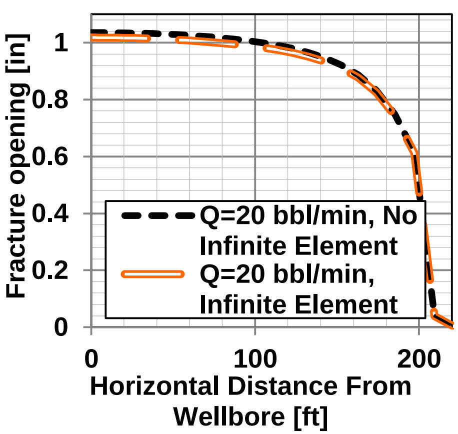
- **Contribution of infinite elements in the solution:**





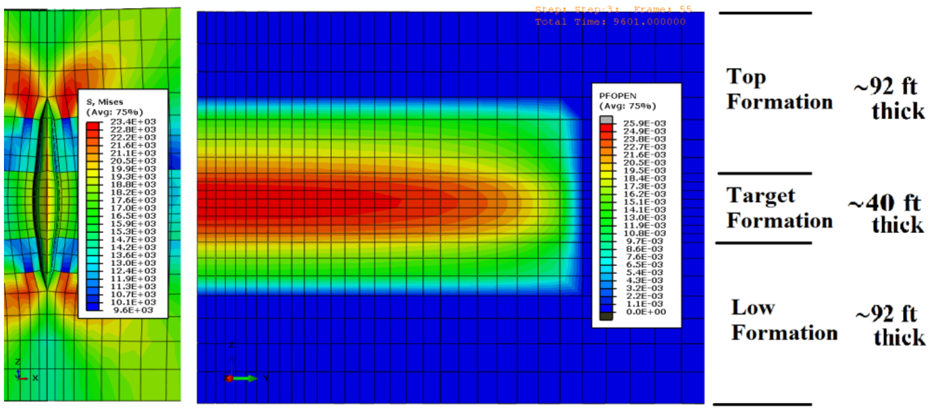
- CIN3D8, or C3D8RP Elements
- Using infinite elements leads to:
  1) the better convergence of the solution because of the quiet boundaries, and
  2) inclusion of the infinite region surrounding our domain of interest.



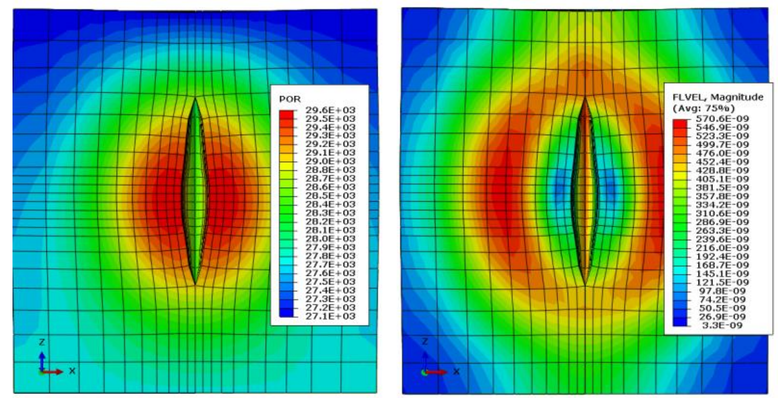


Results: Planar CZM (1/8)

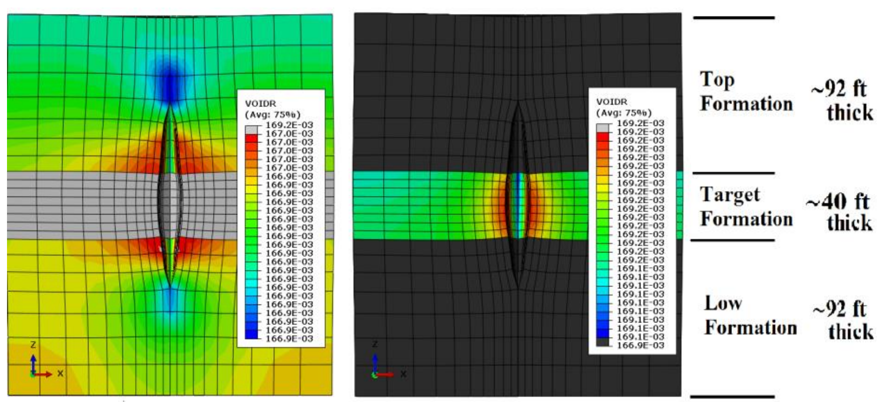
- **Single Fracture Sample Solutions:**
  - **Mises Stress and Fracture Opening**



  - **Pore Pressure and Fluid Velocity**

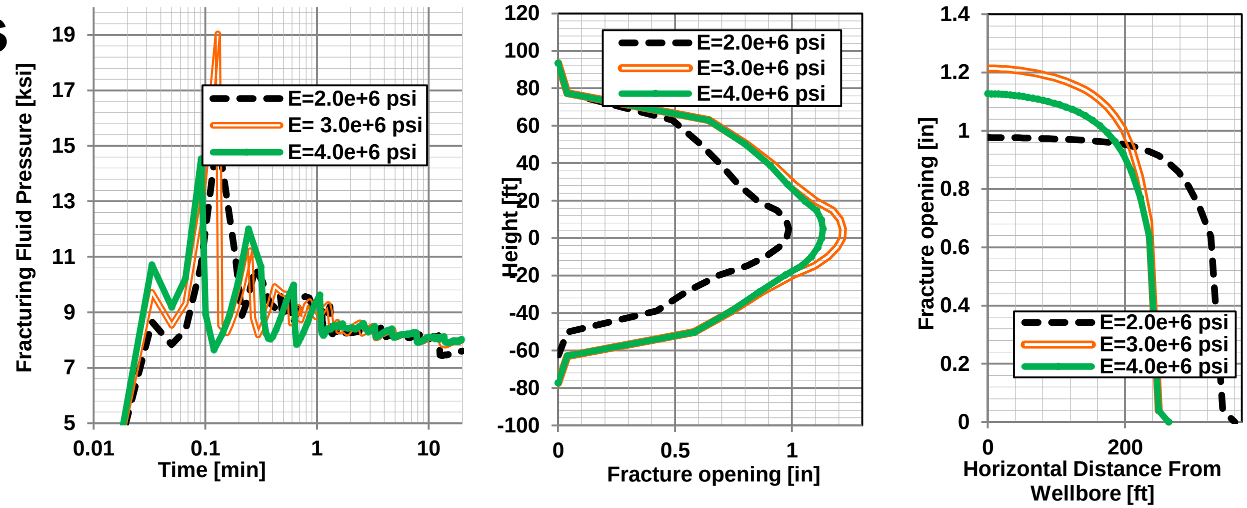


  - **Void ratio; differentiated due to stress states**

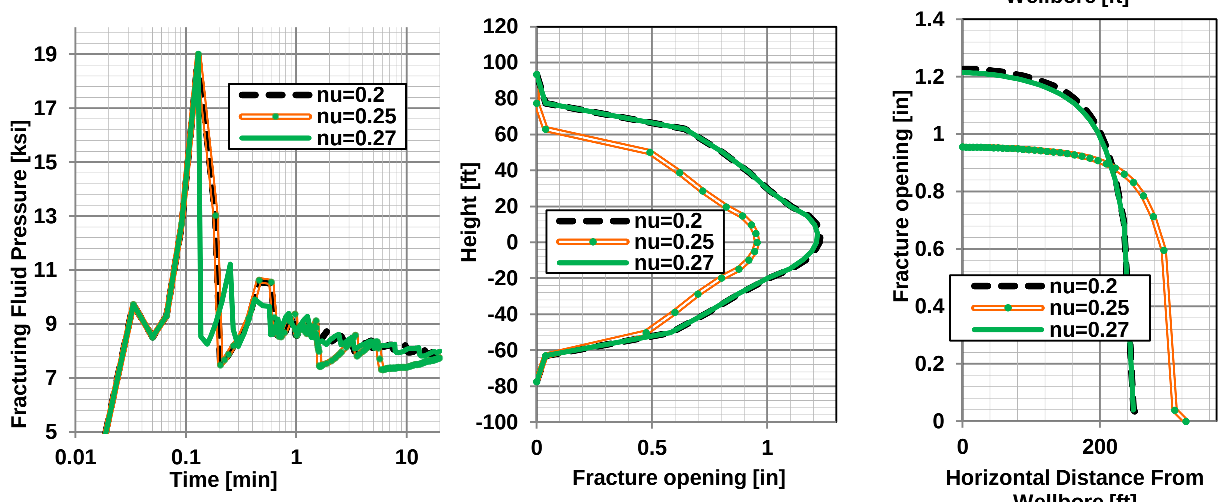


Results: Planar CZM (2/8)

- **Stimulation controlling factors:**
  - **Young's Modulus**
    - Significance of Young's modulus in fracture characteristics



  - **Poisson's Ratio**
    - Significance of Poisson's ratio in fracture characteristics

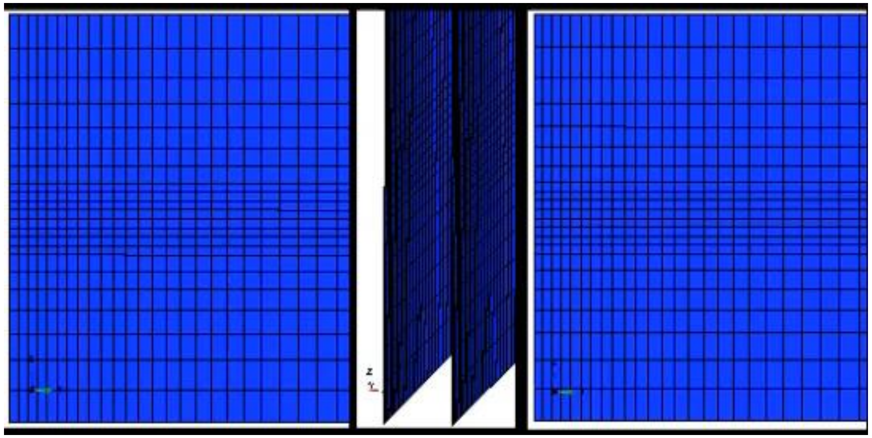


Results: Planar CZM (3/8)

- **Sequential Double Fracture Results**

  - **Spacing 33 ft**

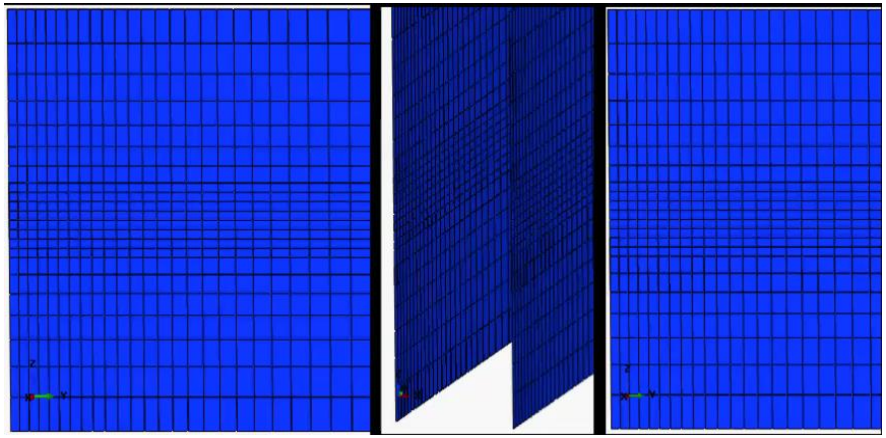
Animation 1: Opening contours



- 1st-stage fracture closure due to the 2nd-stage fracture growth; Disconnection of the 1st-stage from wellbore
- Upward and downward growth

  - **Spacing 66 ft**

Animation 2: Opening contours



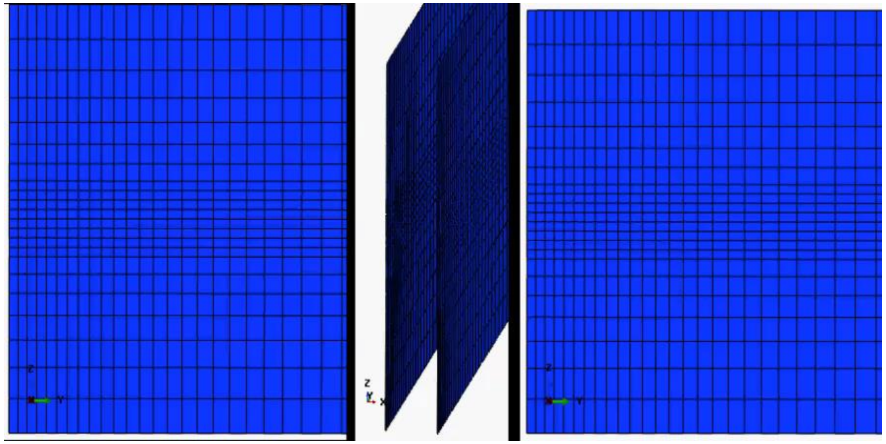
- Worse 1st-stage fracture closure due to the 2nd-stage fracture growth; Disconnection of the 1st-stage from wellbore
- More identical height growth

Results: Planar CZM (4/8)

- **Simultaneous Double Fracture Results**

  - **Spacing 33 ft**

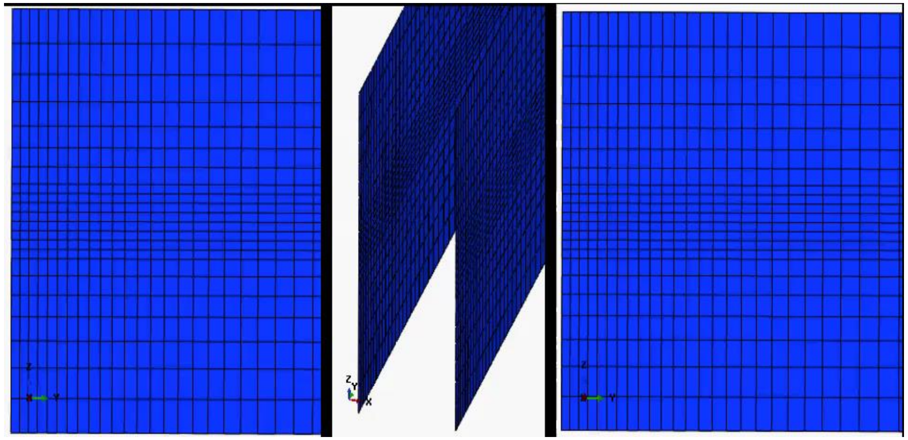
Animation 3: Opening contours



- Better fracture connection to the wellbore compared to the sequential cases
- Upward and downward growth and different growth in length

  - **Spacing 66 ft**

Animation 4: Opening contours

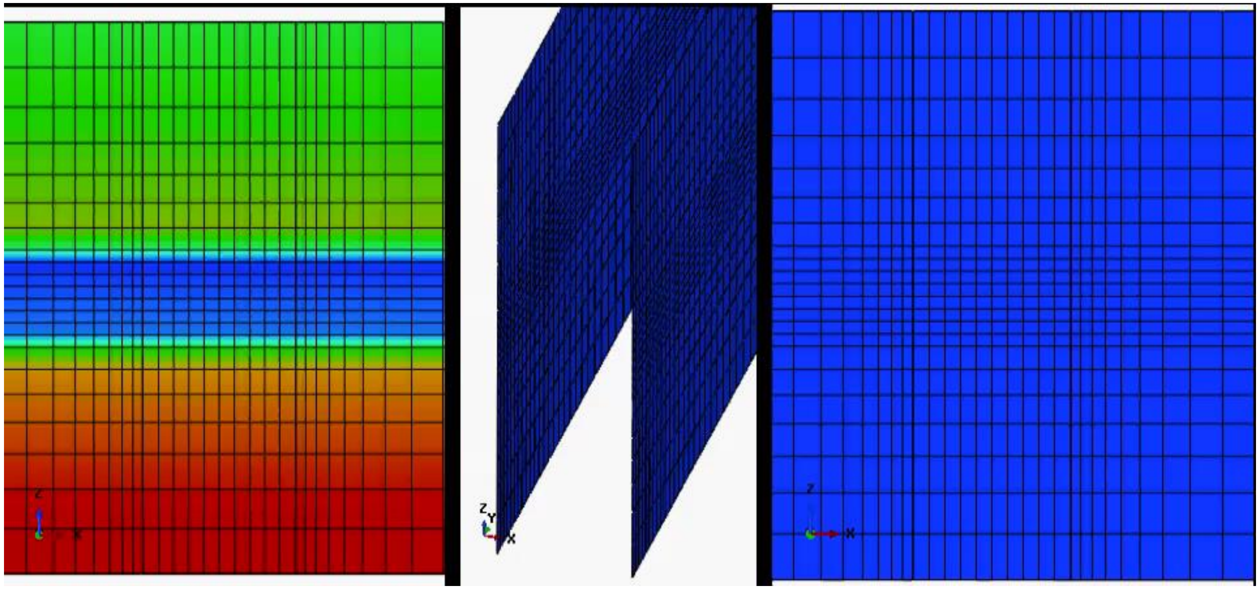


- The best fracture geometry and connection to the wellbore compared to the other cases
- Almost even height and length growth

Results: Planar CZM (5/8)

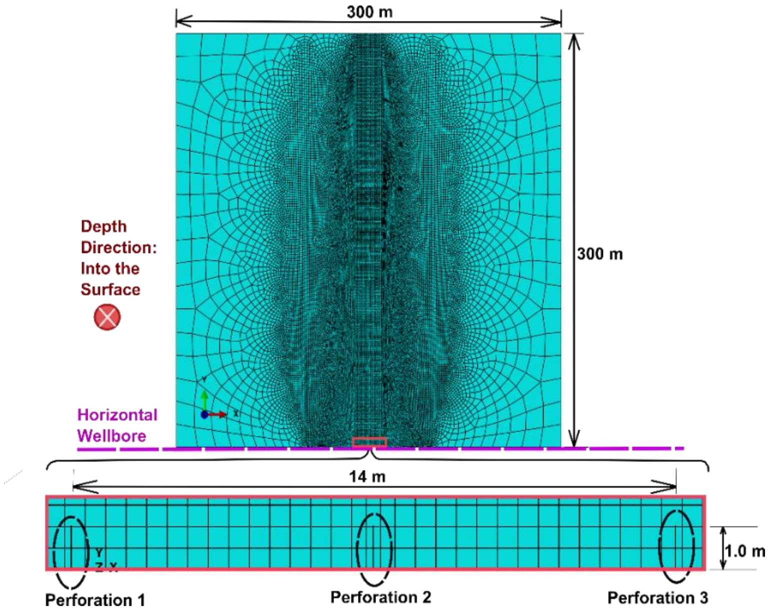
- **Simultaneous Double Fracture Results**
  - **Spacing 66 ft**

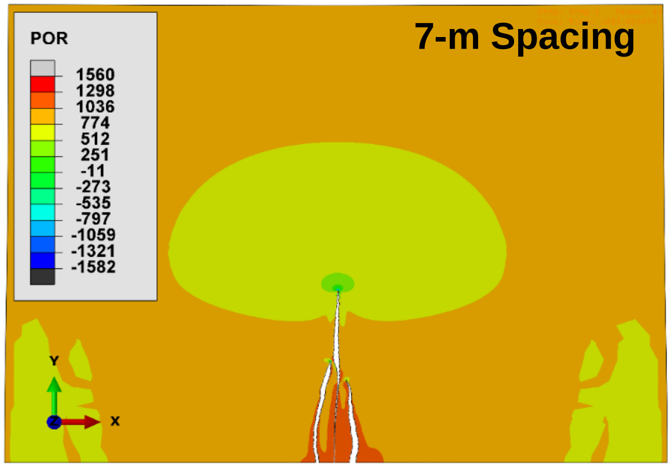
Animation 5: Void R, Opening, S13 contours



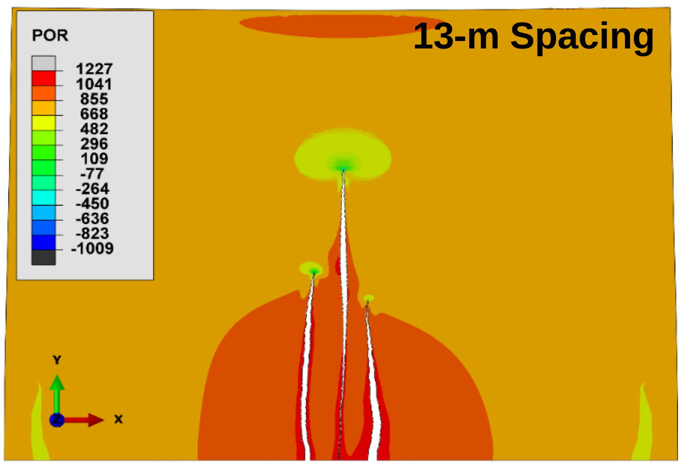
- More porosity and permeability modification due to leak-off for the upper and lower layers

Results: XFEM-based CZM (6/8)

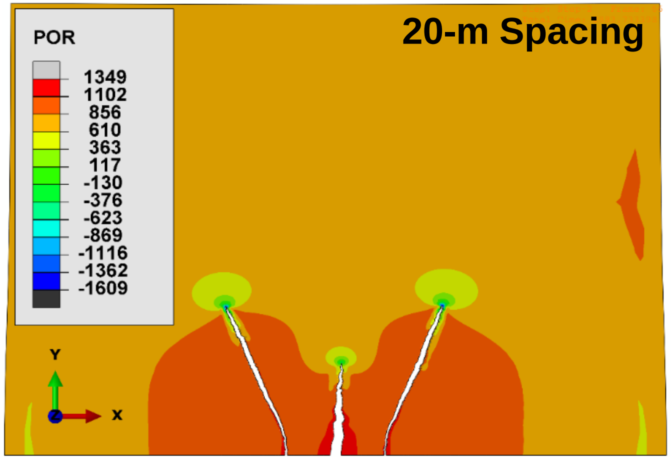




Fracture Coalescence

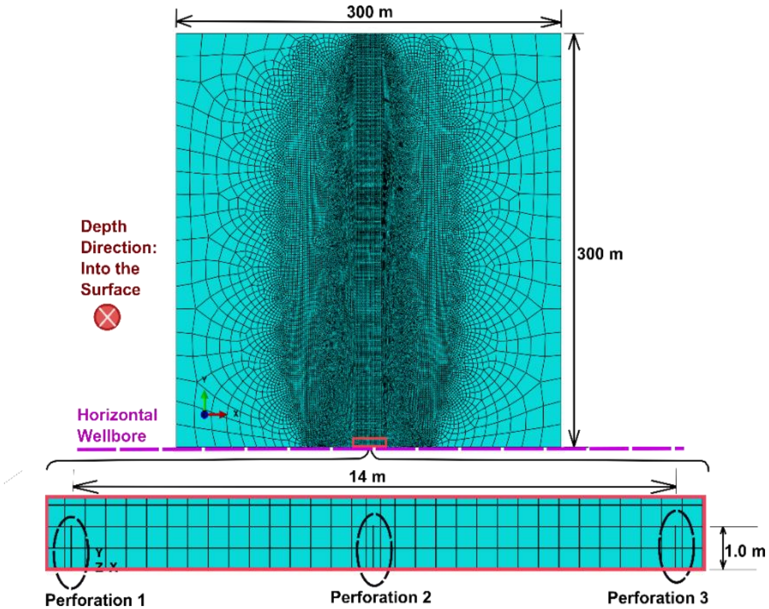


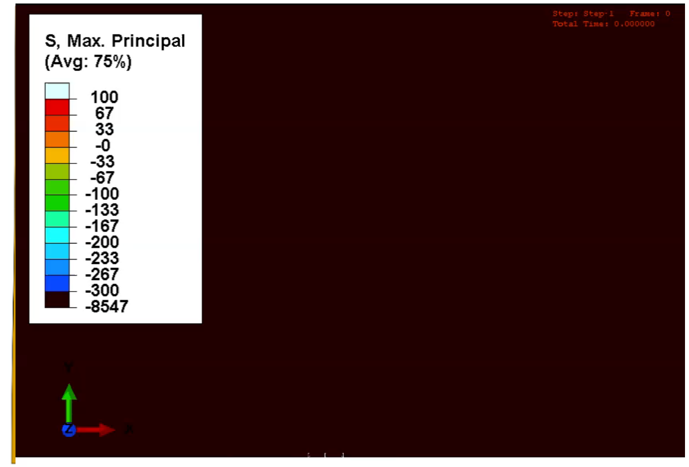
Almost parallel fractures



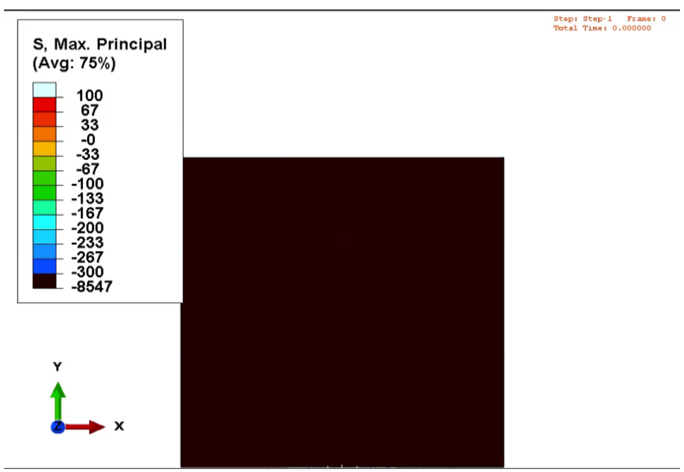
Outward-deviating fractures

Results: XFEM-based CZM (7/8)

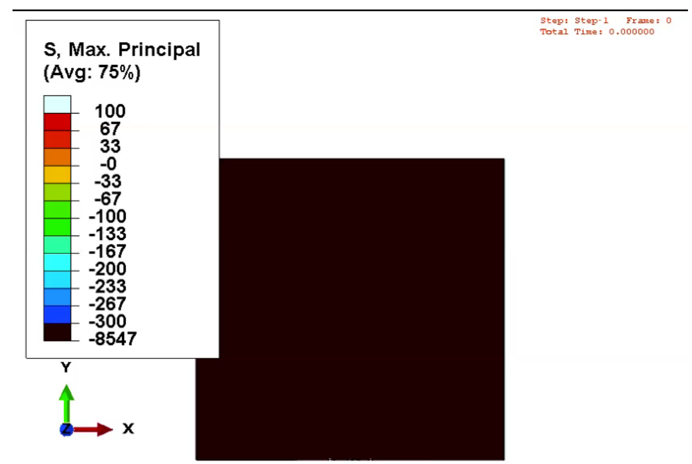




Fracture Coalescence



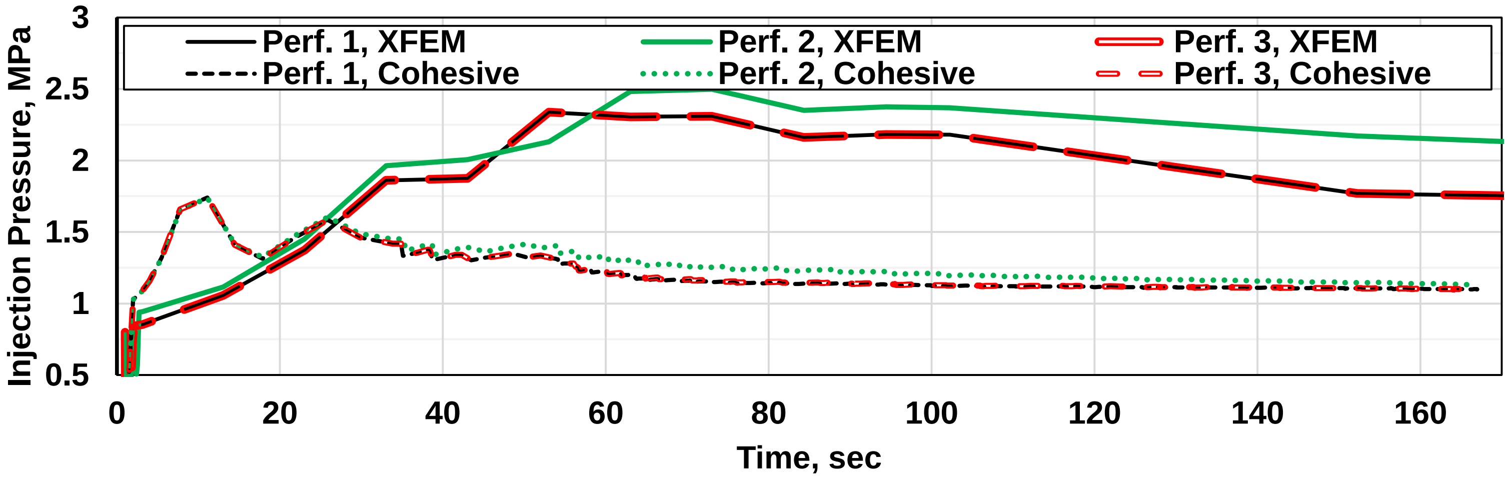
Almost parallel fractures

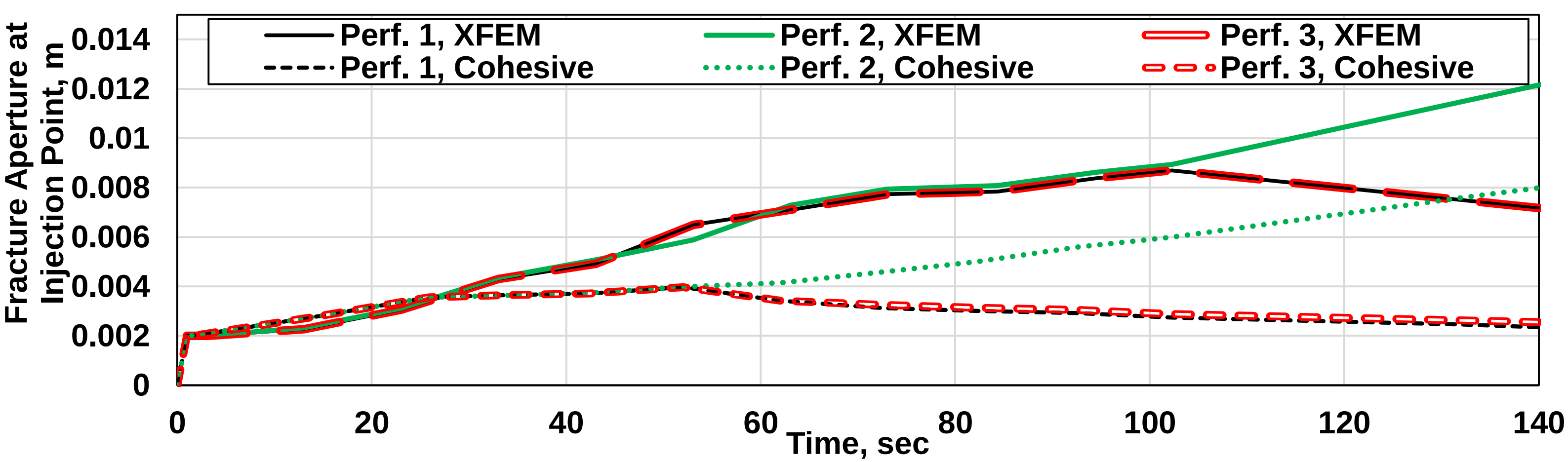


Outward-deviating fractures

Results: Comparison (8/8)

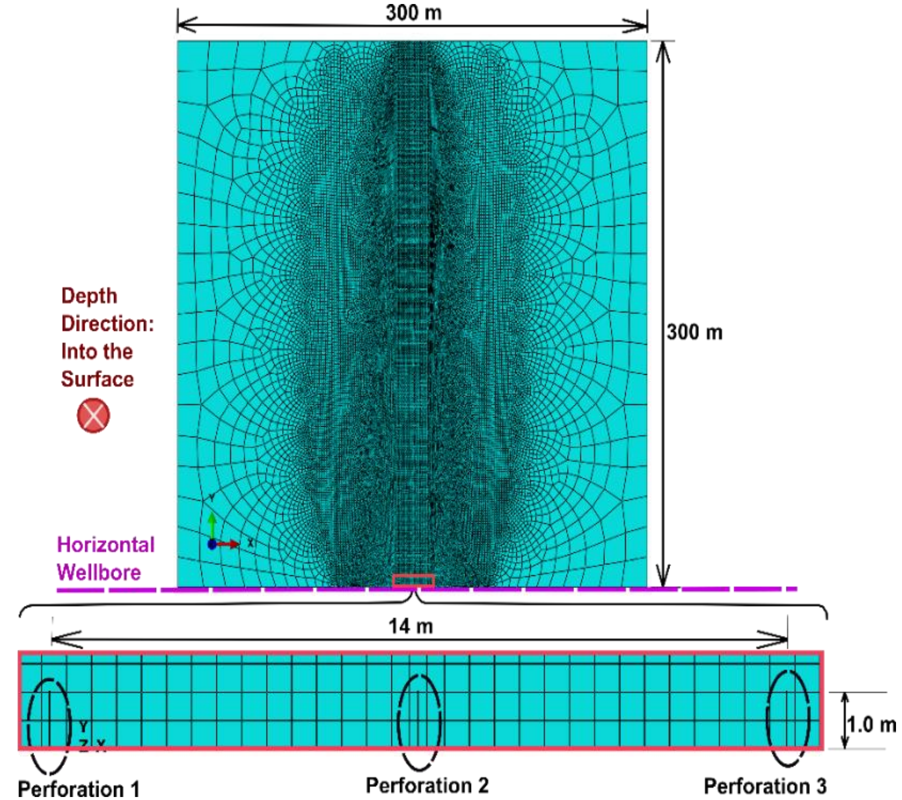
- **Results from CZM and XFEM-based CZM for 7-m spacing**





Results: Computational remarks in using XFEM in Abaqus (9/8)

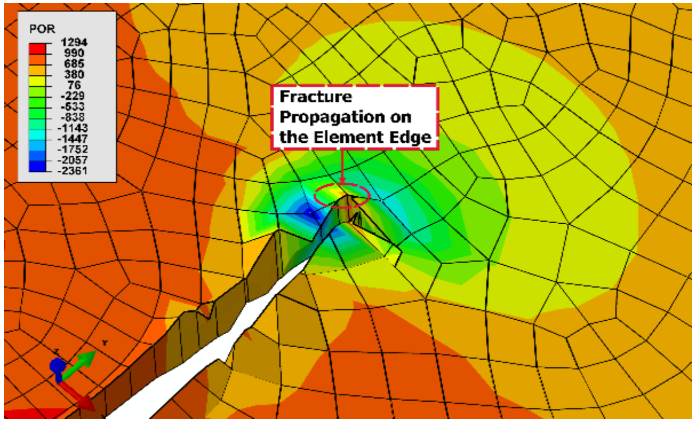
- The removal of the crack tip enrichment by complete crossing of the elements.
- Well-located initial cracks.
- Only one crack is allowed to cross an element.
- Excluding hotspots in the enrichment zones.



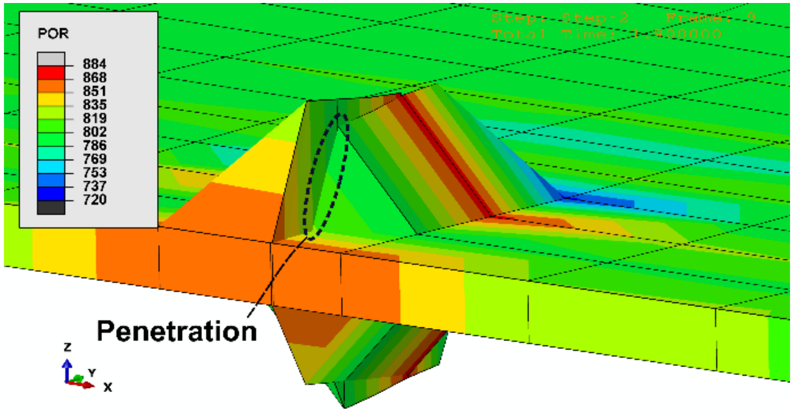
- Locally refined mesh around the fracture propagation path.
- Mixed-mode fracture propagation highly sensitive to boundary conditions.

Results: Computational remarks in using XFEM in Abaqus (9/8)

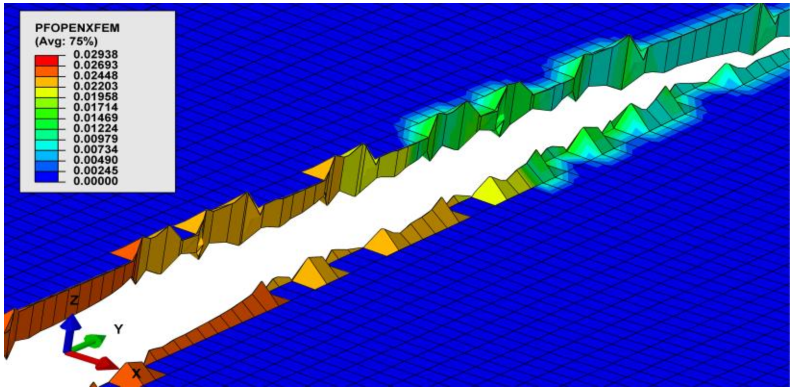
- Diverging solution by fracture propagation on the edge of an element



- Crossing fewer elements by the initial fractures for fast early-time convergence.

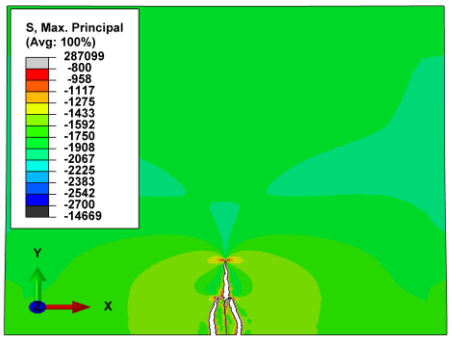


- Freedom of the edge phantom nodes to move out of the boundaries

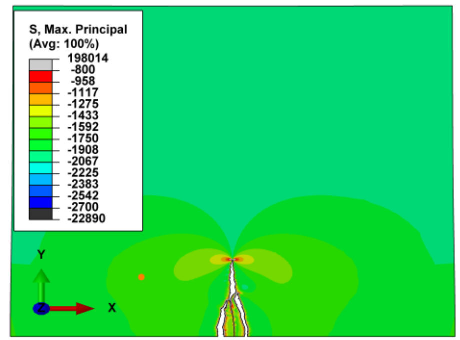


Results: Parametric Study (10/8)

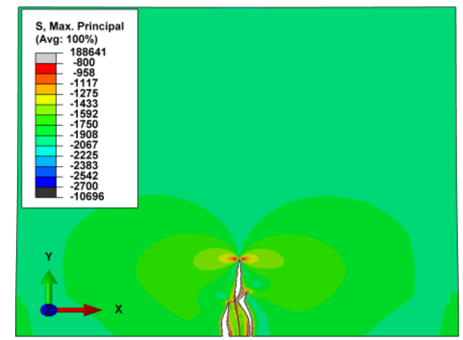
- **Stress contrast, 7-meter spacing, Min. Horiz. 10 Mpa**



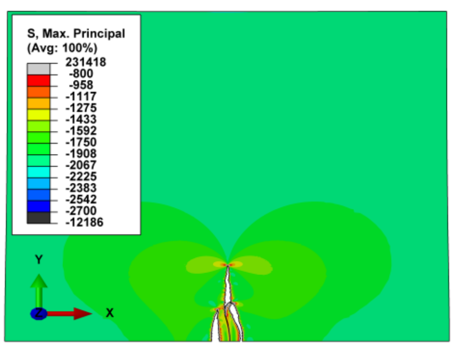
$S_{H,max,tot} = 9.9$ MPa



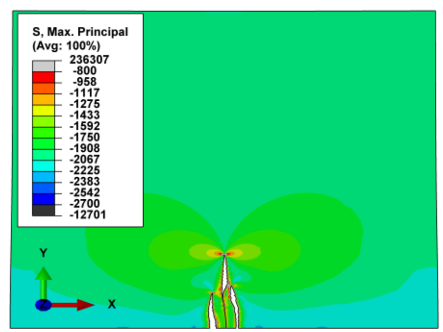
$S_{H,max,tot} = 10.0$ MPa



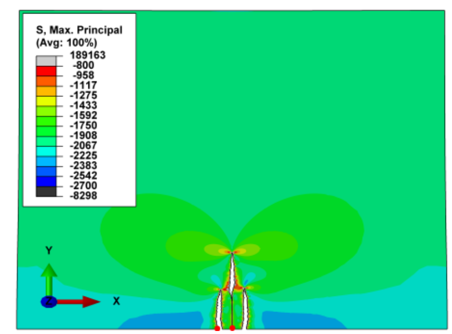
$S_{H,max,tot} = 10.1$ MPa



$S_{H,max,tot} = 10.2$ MPa



$S_{H,max,tot} = 10.5$ MPa

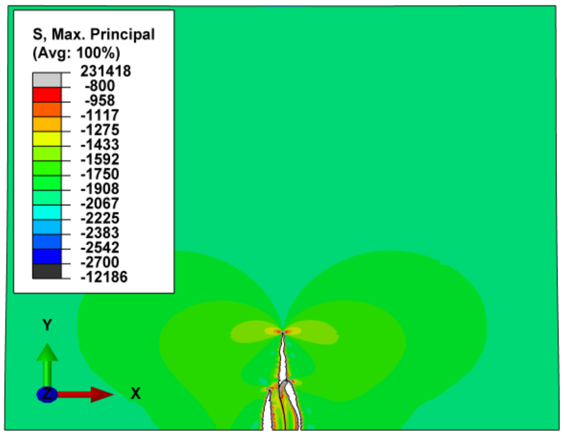


$S_{H,max,tot} = 11.0$ MPa

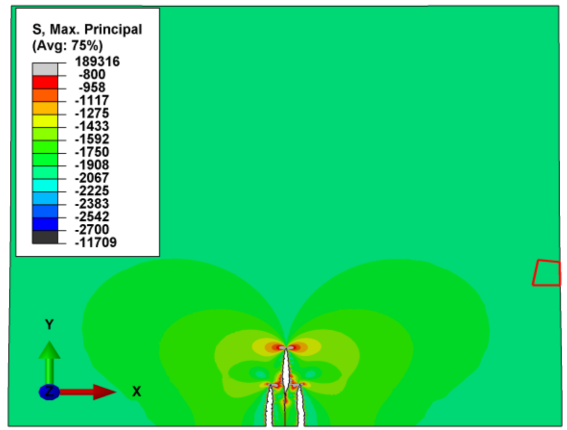
- **matching injection pressure and fracture aperture at the injection point for various perforations at various stress contrast.**

Results: Parametric Study (11/8)

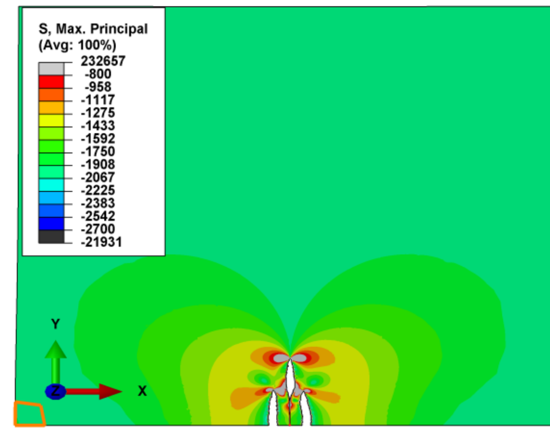
- **Injection rate, for 7-meter spacing, and max. and min. horiz. stresses equal to 10.2 and 10 MPa**



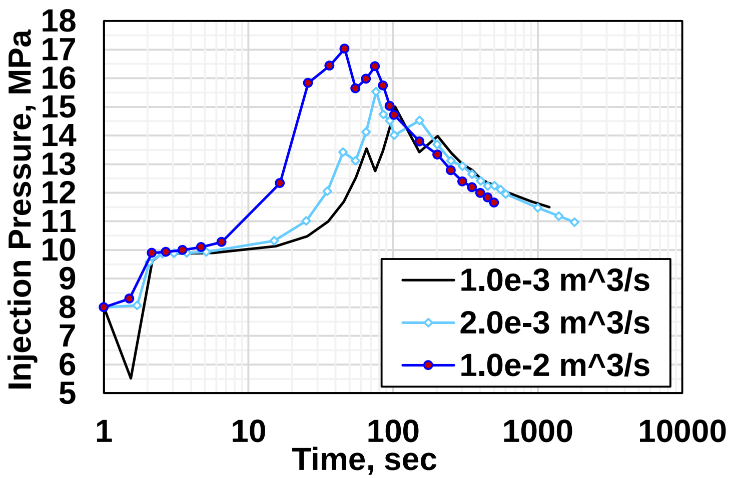
$0.001\ m^3/s$ /perforation

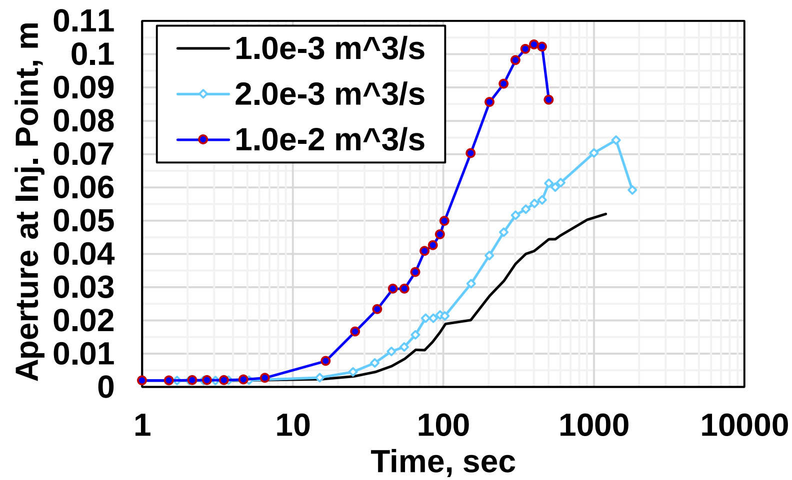


$0.002 m^3/s$ /perforation



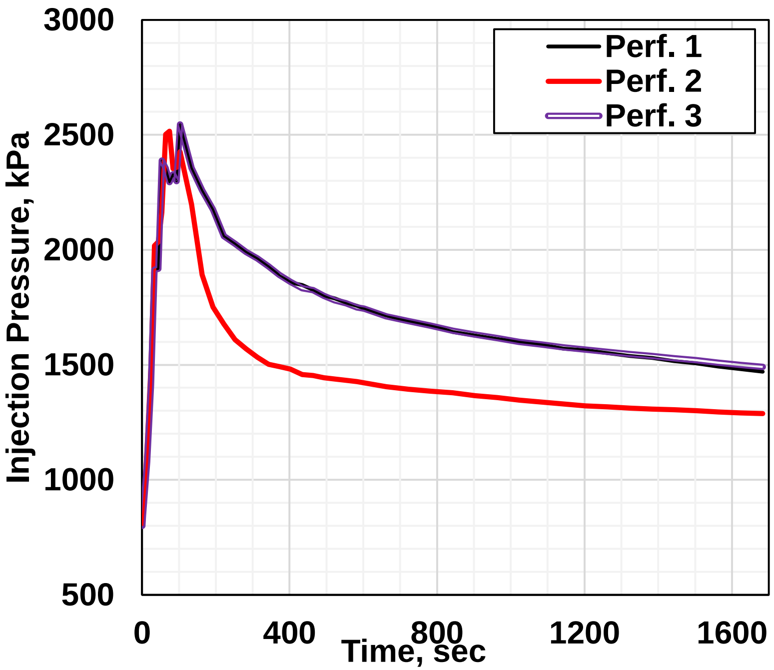
$0.01\ m^3/s$ /perforation

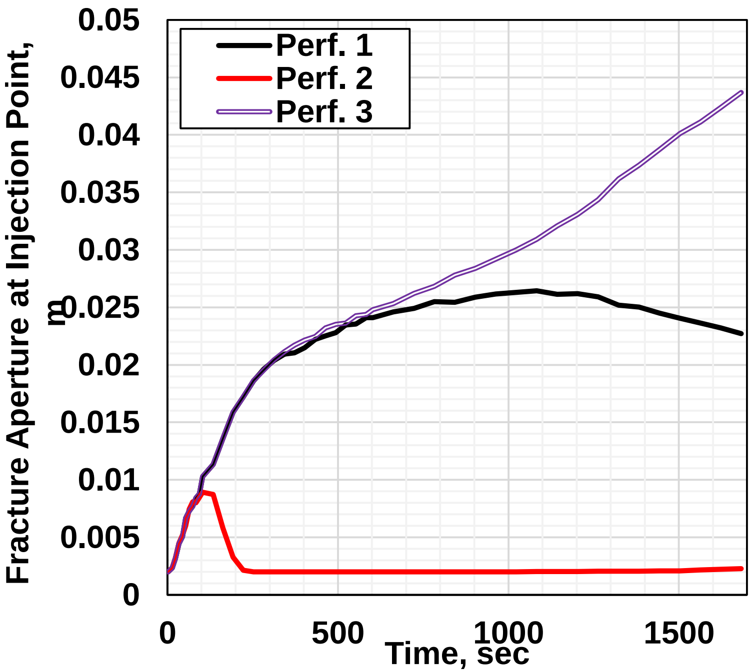




Results: Future work (11/8)

- **Uneven left and right fracture propagation for 7-meter spacing**





Summary and Conclusion (1/1)

- Using a fully coupled pore pressure-stress analysis, we solved 3D single-, double-, and triple-stage hydraulic fracturing problems using planar CZM and XFEM-based CZM, both advantageous with respect to LEFM for quasibrittle rocks.
- We inspected the sensitivity of the pumping pressure and fracture opening to the target formation's Young's modulus and Poisson's ratio.
- Mechanical interactions or stress shadowing effects of closely spaced hydraulic fractures may lead to the following:
  - Coalescence, and outward deviation of side fractures in XFEM.
  - Shorter growth and closure of the middle fracture at injection point in XFEM.
  - 1^{st} fracture closure due to the growth of the 2^{nd} one, severe upward or downward growth, and higher injection pressure for the subsequent stages.
- XFEM-based CZM gives arbitrary solution-dependent path in contrast to CZM which gives growth on a pre-defined plane.
- Building a model and grid dependence analysis using XFEM-based CZM are easier than CZM due to the element type, initialization and element crossing.

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Thanks for your attention

Any Questions?